THE CNST NEWS

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FROM THE DIRECTOR

In this issue's Director's Column, I want to briefly describe the CNST's research in nanoscale optics and photonics, which I will refer to as nanophotonics. If you are familiar with the CNST, you know that we support the development of nanotechnology over a very broad portfolio of interest areas. Within the NanoLab, we tend to collect our research topics in three theme areas, nanofabrication and nanomanufacturing, future electronics, and energy. Of course, while these areas provide homes for some of the most popular nanotechnology topics, they are not intended to restrict, in any way, our ability to make contributions in other areas.

Below this top level of our research taxonomy, you'll find other areas of common interest that involve more than one CNST project. Nanophotonics is just one such area. It is important to us because nanostructures can fundamentally alter the propagation and confinement of light in comparison to what we are used to in bulk materials. Confining light to small spaces is not only essential if you want to leverage the advantages of optical techniques to interrogate systems at the nanoscale, but can also result in extremely large optical intensities that enhance the performance of devices based on the interaction of light with materials. For example, the constantly expanding need for sensors, both the low-cost and high precision variety, is just one of many drivers for research in the area of nanophotonics.

Hence, we have created a sub-theme of nanophotonics which spans both the CNST NanoLab and NanoFab. A community of interest has brought together experts in design/simulation, nanofabrication, and nanoscale measurement. Using finite-difference time-domain and finite-element methods, the behavior of light is being reliably modeled to predict its interaction with nonlinear optical materials and resident mechanical structures. Nanophotonics specialists within the CNST NanoFab and NanoLab have acquired tools and developed processes specific to the fabrication of nanophotonics devices. And, a wide array of advanced tools have been developed within the CNST NanoLab to provide the necessary measurement technology to characterize the performance and operation of a broad array of nanophotonics devices.

Our goal has been to develop a specialty in nanophotonics that spans the space from modeling, to fabrication, to performance testing, to manufacturing. Achievements to date include understanding radiation pressure forces in dielectric media and metamaterials, manipulating the spectrotemporal properties of quantum states of light, mapping the optical modes of nanophotonics devices, and testing the motion of complex mechanical systems through optical nanoscopy. Work is continuing on force and displacement sensors, nanomechanical transducers, electromechanically tunable plasmonic modulators, quantum optical light sources, frequency conversion hardware, and nanophotonics-based, compact time and frequency metrology tools.

We plan to provide more detailed information on our program in nanophotonics in the next update of the CNST website. In the interim, if you are interested in a possible collaboration with one of our nanophotonics experts or in making use of the tools and processes we have been developing to support nanophotonics within our NanoFab, please contact me for further information.

Robert Celotta

ULTRASONICALLY PROPELLED NANORODS SPIN DIZZYINGLY FAST

Vibrate a solution of rod-shaped metal nanoparticles in water with ultrasound and they will spin around their long axes like tiny drill bits. CNST researchers have clocked their speed and discovered that it is dizzyingly fast. Spinning at up to 150,000 revolutions per minute (RPM), these nanomotors rotate 10 times faster than any nanomotor in liquid previously reported.

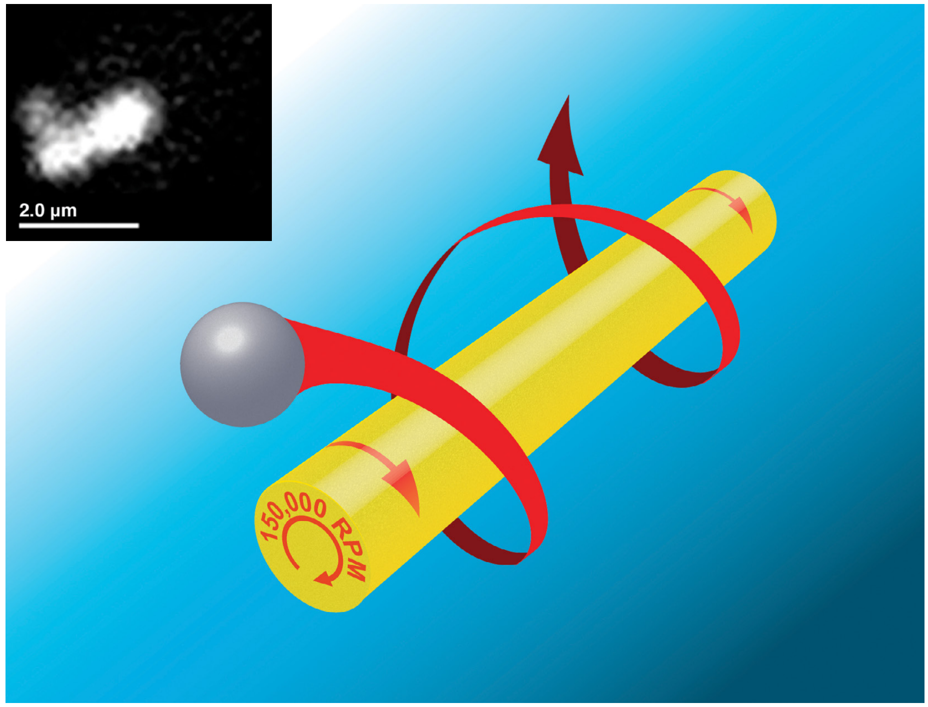
The discovery of this remarkably high rate of rotation has opened up the possibility that they could be used not only for moving around inside the body—the impetus for the research—but also for high-speed machining and mixing.

Scientists have been studying how to make nanomotors move around in liquids for the past several years. A group at Penn State looking for a biologically friendly way to propel nanomotors first observed that metal nanorods were moving and rotating in response to ultrasound in 2012. Another group at the University of California San Diego then directed the metal rods' forward motion using a magnetic field. The Penn State group then demonstrated that these nanomotors could be propelled inside of a cancer cell.

But no one knew why or how fast the nanomotors were spinning. The latter being a measurement problem, the CNST researchers worked with the Penn State group to solve it.

"If nanomotors are to be used in a biological environment, then it is important to understand how they interact with the liquid and objects around them," says Nanofabrication Research Group Project Leader Samuel M. Stavis. "We used nanoparticles to trace the flow of water around the nanomotors, and we used that measurement to infer their rate of rotation. We found that the nanomotors were spinning surprisingly rapidly."

The CNST team clocked the nanomotors' rotation by mixing the 2-micrometer-long, 300-nanometer-wide gold rods with 400-nanometer-diameter polystyrene beads in water and putting them between glass and silicon plates with a speaker-type shaker beneath. They then vibrated the shaker at an ultrasonic tone of 3 megahertz—much too high for you or your dog to hear—and watched the motors and beads move.



Schematic of a gold nanorod (yellow) propelled by ultrasound in water, rapidly rotating around its long axis and advecting a tracer nanoparticle (gray) around it. The NIST scientists determined the rate of rotation of the nanorod by measuring and modeling the motion of the nanoparticle (red arrow). **Inset:** Micrograph of the nanorod-nanoparticle system.

As the motors rotate in water, they create a vortex around them. Beads that get close get swept up by the vortex and swirl around the rods. By measuring how far the beads are from the rods and how fast they move, the group was able to work out how quickly the motors were spinning—with an important caveat.

"The size of the nanorods is important in our measurements" says CNST/UMD Postdoctoral Researcher Andrew Balk. "We found that even small variations in the rods' dimensions cause large measurement uncertainties, so they need to be fabricated as uniformly as possible for future studies and applications."

According to the researchers, the speed of the nanomotors' rotation seems to be independent of their forward motion. Being able to control the "speed and feed" of the nanomotors independently would open up the possibility that they could be used as rotary tools for machining and mixing.

Future avenues of research include trying to discover exactly why the motors rotate and how the vortex around the rods affects their interactions with each other.

Kilohertz rotation of nanorods propelled by ultrasound, traced by microvortex advection of nanoparticles, A. L. Balk, L. O. Mair, P. P. Mathai, P. N. Patrone, W. Wang, S. Ahmed, T. E. Mallouk, J. A. Liddle, and S. M. Stavis, *ACS Nano* **8**, 8300-8309 (2014).

NEW MICROSCOPE USES LASER-COOLED LITHIUM IONS

In an effort to extract more information about nanomaterials and nanostructures, CNST researchers have built the first low-energy focused ion beam (FIB) microscope that uses a lithium ion source. The team's approach opens up the possibility of creating a whole category of FIBs using any one of up to 20 different elements, greatly increasing the options for imaging, sculpting, or characterizing materials.

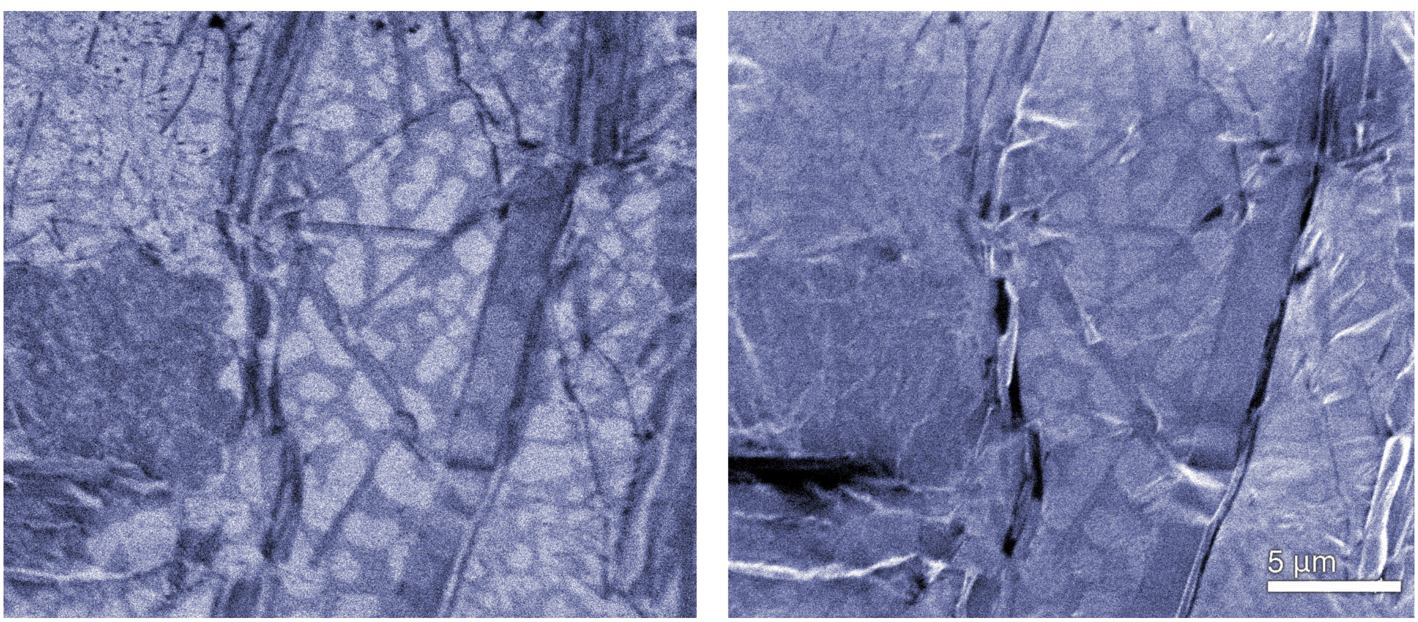
Although the new microscope's resolution isn't yet as good as a SEM or a helium ion microscope (HIM), it can image nonconductive materials and can more clearly visualize the chemical composition on the surface of a sample than conventional SEMs and FIBs. And, the researchers have shown that by analyzing the energy with which the ions scatter, the microscope should be able to not only see that adjacent materials are chemically different, but also identify the elements that make them up.

The researchers made their first low-energy FIB using lithium ions in 2011. Since then, they have been working to refine the technique to increase the beam's brightness and collimation. The new instrument first cools a gas of neutral lithium atoms to a temperature of about 600 microkelvins using lasers and a magneto-optical trap (MOT) to hold the atoms. Another laser ionizes the atoms and then electric fields accelerate them, straightening out their flight and focusing the beam on a target. The NIST FIB can produce lithium ion beams with energies in the range of 500 electron volts to 5,000 electron volts (for comparison, HIMs work best at 30,000 electron volts). The NIST team can reduce the beam's energy even further, but repulsive interaction effects at the source limit how small they can focus the beam when the accelerating field is weaker.

The team also demonstrated how their microscope could help to solve a common problem in nanoimprint lithography, a process for stenciling patterns on silicon chips. This technique requires etching into the silicon through the spaces in the lithography stencil to transfer the pattern. "Before manufacturers can etch the silicon, they have to make sure the spaces are free of chemical residue," says McClelland. "Commonly they use a process called plasma etching to clean that residue off, but they have to be careful not to overdo it or they can damage the substrate and ruin the chip. Our FIB scope could check to see if the plasma has done its work without damaging the chip. A scanning electron microscope couldn't do this because it's difficult to see the thin residue, and the high energy beam is likely to charge up or melt the stencil and make the problem worse."

The group has big plans for the microscope. They are planning to try to better explain how lithium batteries work by injecting lithium ions into the materials and watching how they affect the behavior of the batteries. A few former members of the group have even started their own company to develop a low-energy cesium FIB for milling and sculpting features on the order of single nanometers, a huge leap in nanofabrication if successful.

"This new form of microscopy that we've developed promises to provide a new tool for nanotechnology with good surface sensitivity, elemental contrast, and high resolution," says McClelland. "The applications range from nanofabrication process control to nanomaterial development and imaging of biomaterials."



Left: A backscattered ion micrograph of lead-tin solder demonstrates how the lithium FIB microscope can clearly distinguish regions of high lead concentration, which appear lighter, from areas of more tin, which appear darker. **Right:** A secondary-electron image mainly captures topological differences.

Scanning ion microscopy with low energy lithium ions, K. A. Twedt, L. Chen, and J. J. McClelland, *Ultramicroscopy* **142**, 24–31 (2014).

RESEARCHERS TAKE FIRST PICTURES OF BABY NANOTUBES GROWING ONE ATOM AT A TIME

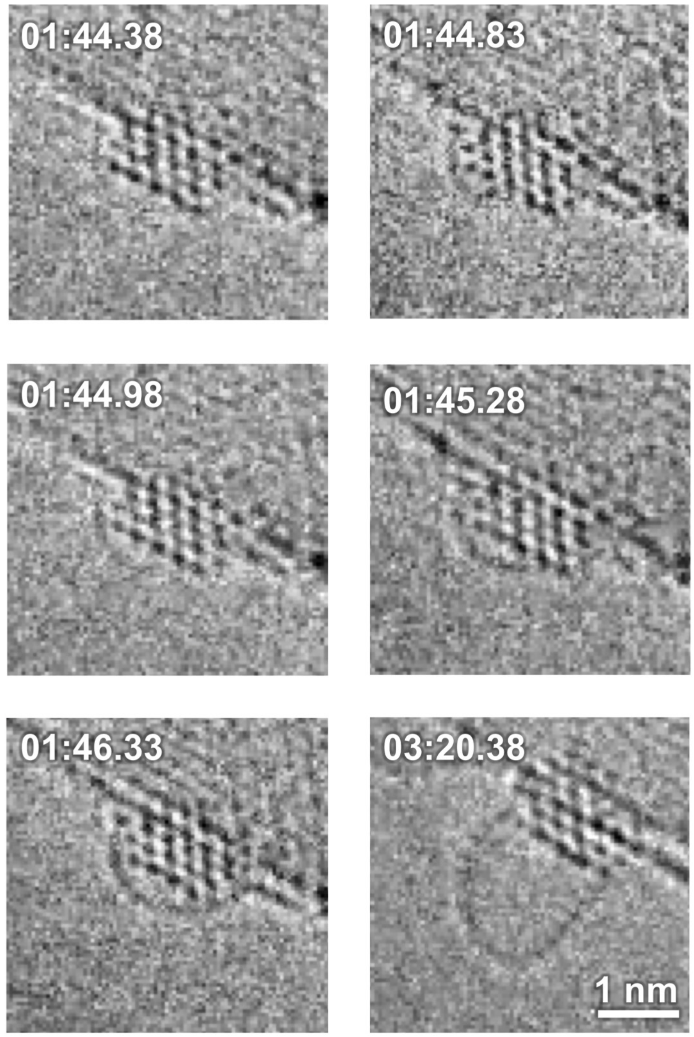
Single-walled carbon nanotubes are loaded with desirable properties. In particular, the ability to conduct electricity at high rates of speed makes them attractive for use as nanoscale transistors. But this and other properties are largely dependent on their structure, and their structure is determined when the nanotube is just beginning to form.

In a step toward understanding the factors that influence how nanotubes form, researchers at the CNST, the University of Maryland, and Texas A&M have succeeded in filming them when they are only a few atoms old. These nanotube "baby pictures" give crucial insight into how they germinate and grow, potentially opening the way for scientists to create them en masse with just the properties that they want.

To better understand how carbon nanotubes grow and how to grow the ones you want, you need to understand the very beginning of the growth process, called nucleation. To do that, you need to be able to image the nucleation process as it happens. However, this is not easy because it involves a small number of fast-moving atoms, meaning you have to take very high resolution pictures very quickly.

Because fast, high-resolution cameras are expensive, the CNST scientists instead slowed the growth rate by lowering the pressure inside their instrument, an environmental scanning transmission electron microscope. Inside the microscope's chamber, under high heat and low pressure, the team watched as carbon atoms generated from acetylene rained down onto 1.2-nanometer bits of cobalt carbide, where they attached, formed into graphene, encircled the nanoparticle, and began to grow into nanotubes.

"Our observations showed that the carbon atoms attached only to the pure metal facets of the cobalt carbide nanoparticle, and not those facets interlaced with carbon atoms," says Nanofabrication Research Group Project Leader Renu Sharma, who led the research effort. "The burgeoning tube then grew above the cobalt-carbon facets until it found another pure metal surface to attach to, forming a closed cap. Carbon atoms continued to attach at the cobalt facets, pushing the previously formed graphene along toward the cap in a kind of carbon assembly line and lengthening the tube. This whole process took only a few seconds."



An environmental scanning transmission electron microscope was used to capture *in situ* time-resolved video images of carbon atoms forming into single wall carbon nanotubes.

According to Sharma, the carbon atoms seek out the most energetically favorable configurations as they form graphene on the cobalt carbide nanoparticle's surface. While graphene has a mostly hexagonal, honeycomb-type structure, the geometry of the nanoparticle forces the carbon atoms to arrange themselves into pentagonal shapes within the otherwise honeycomb lattice. Crucially, these pentagonal irregularities in the graphene's structure are what allows the graphene to curve and become a nanotube.

Because the nanoparticles' facets also appear to play a deciding role in the nanotube's diameter and chirality, or direction of twist, the group's next step will be to measure the chirality of the nanotubes as they grow. The group also plans to use metal nanoparticles with different facets to study their adhesive properties to see how they affect the tubes' chirality and diameter.

Nucleation of graphene and its conversion to single-walled carbon nanotubes, M. Picher, P. A. Lin, J. L. Gomez-Ballesteros, P. B. Balbuena, and R. Sharma, *Nano Letters* **14**, 6104–6108 (2014).

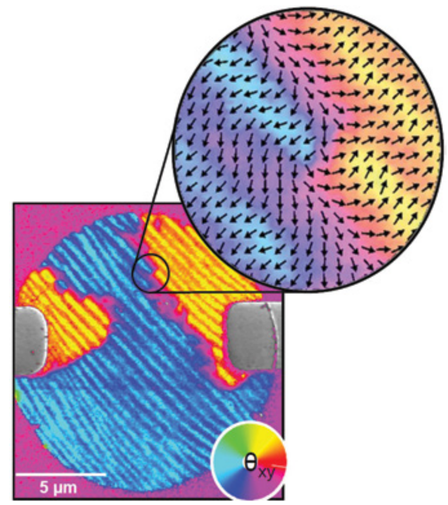
SIMULTANEOUS IMAGING OF FERROMAGNETIC AND FERROELECTRIC DOMAINS

An international team led by researchers from the CNST have discovered a new way to simultaneously image both the ferromagnetic and the ferroelectric domain structures of multilayer devices in which a ferromagnetic film is grown on a ferroelectric substrate. These structures have attracted significant recent interest due to their ability to efficiently use voltage to change the magnetization in low-energy magnetic devices.

The researchers' technique uses a scanning electron microscope (SEM) to provide a quantitative picture of how the ferromagnetic and ferroelectric structures interact. The technique simultaneously measures the SEM's low energy secondary electrons and high energy elastically backscattered electrons. The low energy electrons probe a sample's outermost few nanometers, with their spin polarization measuring the magnetization direction in the ferromagnetic surface film. The backscattered electrons probe deeper into the material's bulk. They detect the sample's crystal structure and reveal its underlying ferroelectric structure. By simultaneously measuring the structures, the technique avoids the systematic errors common to methods requiring multiple measurements taken under different conditions and at different times.

The NIST researchers demonstrated the technique using samples provided by collaborators from the University of California, Berkeley; University of Maryland, College Park; Rutgers University; and ETH, Zurich. These samples included bismuth ferrite and barium titanate substrates coated with ferromagnetic films and had a range of ferroelectric/ferromagnetic coupling strengths. The films ranged in thickness from a couple of atomic layers to 100 nm and were made with various compositions.

The initial positive results have attracted interest from other outside facility users, and the CNST group is currently measuring a new series of samples. The researchers are attempting to image wired devices in order to determine the feasibility of using voltage controlled magnetic switching in working devices.



Scanning electron microscopy with polarization analysis (SEMPA) image of a 15 µm-diameter cobalt iron disc on a bismuth ferrite substrate. The image shows the measured in-plane magnetization direction, $Ø_{xy}$. The magnetization direction is given by the colors in the color wheel shown in the $Ø_{xy}$ image and by the arrows in the magnified inset.

Simultaneous imaging of the ferromagnetic and ferroelectric structure in multiferroic heterostructures, J. Unguris, S. R. Bowden, D. T. Pierce, M. Trassin, R. Ramesh, S.-W. Cheong, S. Fackler, and I. Takeucnı, *APL Materials* **2**, 076109 (2014).

DESIGN GUIDELINES FOR USING SURFACE PLASMON POLARITONS IN SOLAR CELLS

CNST researchers have established guidelines for using surface plasmon polaritons (SPPs) to improve absorption in both photovoltaic or photoelectrochemical cells used for energy conversion. In both types of photocells, SPPs (electromagnetic waves that travel along a metal-semiconductor interface) have the potential to increase the amount of light absorbed in the active material layer, improving the overall efficiency of light collection in solar energy devices.

The researchers have laid out a framework for calculating the maximum achievable efficiency for any arbitrary material of known permittivity (a measure of how an electric field affects a semiconducting or dielectric medium). In SPP-enabled photocells, a metal, such as gold, that supports SPPs is coated with a semiconductor, such as silicon, gallium arsenide, or titanium dioxide. Light absorption in the semiconductor material is expected to increase when SPPs concentrate the electromagnetic field at the interface between the metal and the semiconductor.

Building on the calculations of Shockley and Queisser (1961), which set a thermodynamic limit to the efficiency of a solar cell, the researchers incorporated solutions for Maxwell's equations, a set of equations that form the foundation of classical electrodynamics, to describe SPPs at the interface between a metal and semiconductor. They were able to derive analytical expressions for the maximum achievable efficiency for photocells that incorporate SPPs.

The team showed that the enhancement depends on the optical properties of the semiconductor material and cannot exceed the thermodynamic limit. They showed that photocells based on cadmium telluride, organic polymer blends, and other materials with small positive real permittivity and large positive imaginary permittivity hold particular promise for improving absorption with SPPs. On the other hand, semiconductors like silicon, gallium arsenide, hematite, and titanium dioxide have inherent optical limitations owing to permittivities that result in a significant fraction of the power of the incoming light being lost in the metal and dissipated as heat.

The researchers believe that their findings will guide the design of future energy devices. Their results will allow researchers to predict whether light trapping strategies will be improved by incorporating SPPs formed by different materials and device geometries.

Design considerations for enhancing absorption in semiconductors on metals through surface plasmon polaritons, C. D. Bohn, A. Agrawal, Y. Lee, C. J. Choi, M. S. Davis, P. M. Haney, H. J. Lezec, and V. A. Szalai, *Physical Chemistry Chemical Physics* **16**, 6084–6091 (2014).

NEW METAMATERIAL GIVES LIGHT A ONE-WAY TICKET

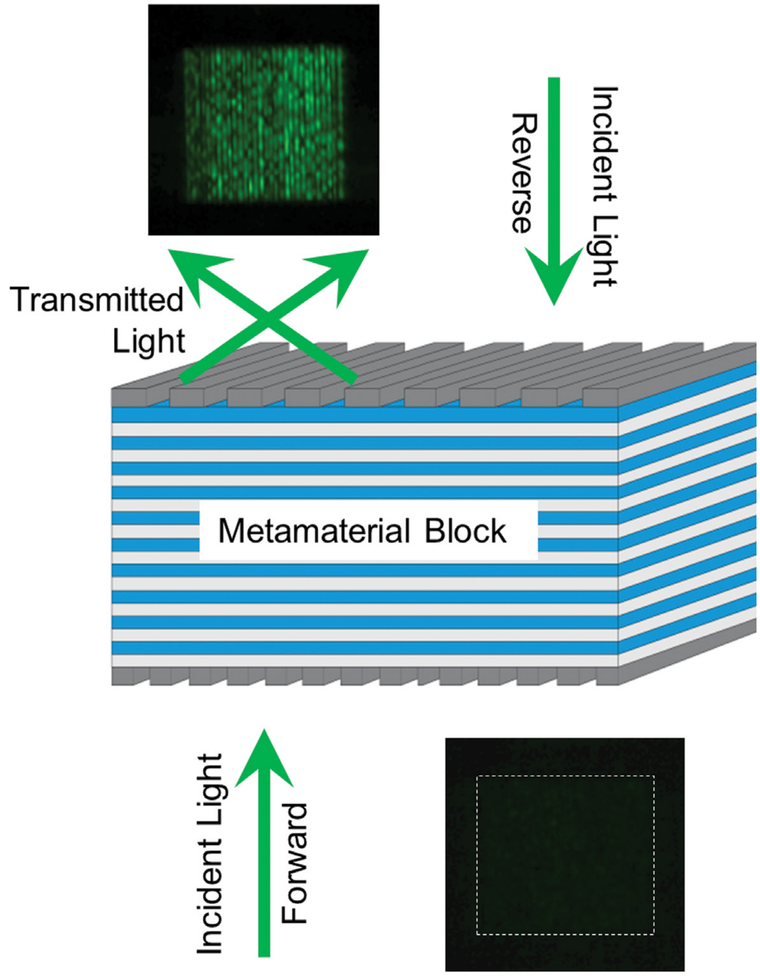
The light-warping structures known as metamaterials have a new trick in their ever-expanding repertoire. CNST researchers have built a silver, glass and chromium nanostructure that can all but stop visible light cold in one direction while giving it a pass in the other. The device could someday play a role in optical information processing and in novel biosensing devices.

In recent years, scientists have designed nanostructured materials that allow microwave or infrared light to propagate in only one direction. Such structures hold potential for applications in optical communication—for instance, they could be integrated into photonic chips that split or combine signals carried by light waves. But, until now, no one had achieved one-way transmission of visible light, because existing devices could not be fabricated at scales small enough to manipulate visible light's short wavelengths. (So-called "one-way mirrors" don't really do this—they play tricks with relative light levels.)

To get around that roadblock, CNST/UMD Postdoctoral Researcher Ting Xu and Nanofabrication Research Group Project Leader Henri Lezec combined two light-manipulating nanostructures: a multi-layered block of alternating silver and glass sheets and metal grates with very narrow spacing.

The silver-glass structure is an example of a "hyperbolic" metamaterial, which treats light differently depending on which direction the waves are traveling. Because the structure's layers are only tens of nanometers thick—much thinner than visible light's 400 to 700 nanometer wavelengths—the block is opaque to visible light coming in from outside. Light can, however, propagate inside the material within a narrow range of angles.

Xu and Lezec used thin-film deposition techniques to build a hyperbolic metamaterial block. Guided by computer simulations, they fabricated the block out of 20 extremely thin alternating layers of silicon dioxide glass and silver. To coax external light into the layered material, the researchers added to the block a set of chromium grates with narrow, sub-wavelength spacing chosen to bend incoming red or green light waves just enough to propagate inside the block. On the other side of the block, the researchers added another set of grates to kick light back out of the structure, although angled away from its original direction.



Schematic of a one-way metamaterial. Forward travelling green light (left) or red light passes through the multilayered block and comes out at an angle due to diffraction off of grates on the surface of the material. Light travelling in the opposite direction (right) is almost completely filtered by the metamaterial and can't pass through.

While the second set of grates let light escape the material, their spacing was slightly different from that of the first grates. As a result, the reverse-direction grates bent incoming light either too much or not enough to propagate inside the silver-glass layers. Testing their structures, the researchers found that around 30 times more light passed through in the forward direction than in reverse, a contrast larger than any other achieved thus far with visible light.

Combining materials that could be made using existing methods was the key to achieving one-way transmission of visible light, Lezec says. Without the intervening silver-and-glass blocks, the grates would have needed to be fabricated and aligned more precisely than is possible with current techniques. "This three-step process actually relaxes the fabrication constraints," Lezec says.

In the future, the new structure could be integrated into photonic chips that process information with light instead of electricity. Lezec thinks the device also could be used to detect tiny particles for biosensing applications. Like the chrome grates, nanoscale particles also can deflect light to angles steep enough to travel through the hyperbolic material and come out the other side, where the light would be collected by a detector. Xu has run simulations suggesting such a scheme could provide high-contrast particle detection and is hoping to test the idea soon. "I think it's a cool device where you would be able to sense the presence of a very small particle on the surface through a dramatic change in light transmission," says Lezec.

Visible-frequency asymmetric transmission devices incorporating a hyperbolic metamaterial, T. Xu and H. J. Lezec, *Nature Communications* **5**, (2014).

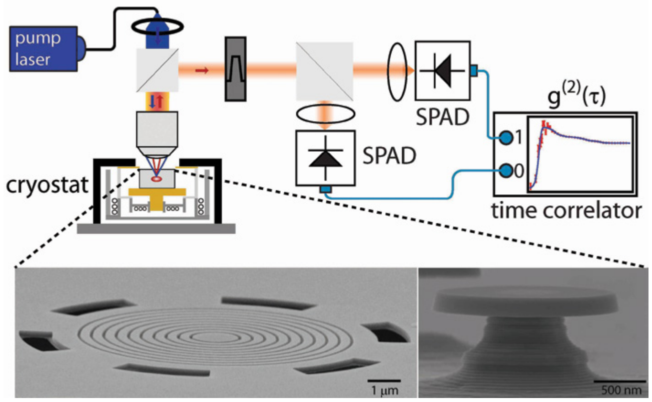
DON'T BLINK! WHY QUANTUM DOTS DISPLAY "FLUORESCENCE INTERMITTENCY"

CNST researchers, working in collaboration with the Naval Research Laboratory, have found that a particular species of quantum dots that weren't commonly thought to blink, do. Although the blinks are short—on the order of nanoseconds to milliseconds—even brief fluctuations can result in efficiency losses that could cause trouble for using quantum dots to generate photons that move information around inside a quantum computer or between nodes of a future high-security internet based on quantum telecommunications. Beyond demonstrating that the dots are blinking, the researchers also suggest a possible cause.

Scientists have regarded quantum dots made of indium arsenide and gallium arsenide (InAs/GaAs quantum dots) to be promising as single photon sources for use in different future computing and communication systems based on quantum technologies. The quantum dots were promising because they appeared to not blink and because they can be fabricated directly into the types of semiconductor optoelectronics that have been developing rapidly over the past few decades.

The research team also thought these quantum dots were emitting steady light perfectly until they came upon one that was obviously blinking (or "displayed fluorescence intermittency," in technical terms). They decided to see if they could find others that were blinking in a less obvious way.

While most previous experiments surveyed the dots in bulk, the team used structures fabricated in the CNST NanoFab to test these dots as they would be used in an actual device. Using an extremely sensitive photon autocorrelation technique to uncover subtle signatures of blinking, they found that the dots blink over timescales from tens of nanoseconds to hundreds of milliseconds. Their results suggest that building photonic structures around the quantum dots—something you'd have to do to make many applications viable—may make them significantly less stable as a light source.



Top: Schematic of the experimental apparatus used to investigate quantum dot blinking. A quantum dot is optically excited using a laser and its fluorescence is collected and split into two paths, each equipped with a single photon avalanche diode (SPAD). A time correlator records the arrival of the photons on each SPAD, from which the autocorrelation function is determined. **Bottom:** SEM images of quantum dot devices, which include a circular grating optical cavity (left) and a microdisk optical cavity (right).

"Most of the previous experimental studies of blinking in InAs/GaAs quantum dots looked at their behavior after the dots have been grown but before the surrounding devices have been fabricated," says Kartik Srinivasan, a Project Leader in the Nanofabrication Research Group. "However, there is no guarantee that a quantum dot will remain non-blinking after the nanofabrication of a surrounding structure, which introduces surfaces and potential defects within 100 nanometers of the quantum dot. We estimate the radiative efficiency of the quantum dots to be between about 50 and 80 percent after the photonic structures are fabricated, significantly less than the near-100 percent efficiency that future applications will require."

According to Marcelo Davanço, another author of the study, future work will focus on measuring dots both before and after device fabrication to better assess whether the fabrication causes the defects thought to generate the blinking. Ultimately, the researchers hope to understand what device geometries will avoid blinking while still efficiently funneling the emitted photons into a useful transmission channel, such as an optical fiber.

Multiple time scale blinking in InAs quantum dot single-photon sources, M. Davanço, C. S. Hellberg, S. Ates, A. Badolato, and K. Srinivasan, *Physical Review B* **89**, 161303 (2014).

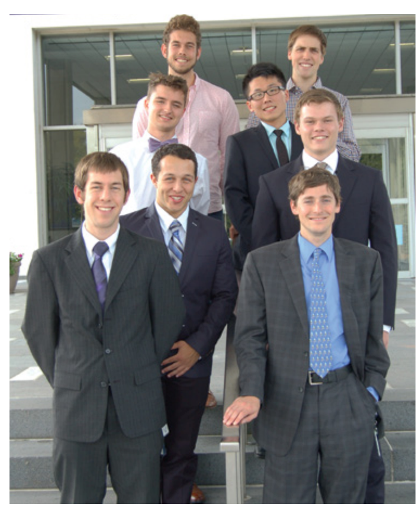
SUMMER STUDENTS WORK WITH LEADING RESEARCHERS AT THE CNST

This past summer, the CNST hosted eleven summer student researchers. Eight Summer Undergraduate Research Fellowship (SURF) students, two research interns, and a CNST Undergraduate Researcher all learned about the latest nanotechnology fabrication and measurement techniques. They participated in a wide variety of research projects ranging from studying lithium ion battery materials and carbon nanotube composites using the CNST's one-of-a-kind lithium ion microscope to developing computer models of the electronic structure of perovskite interfaces. The SURF program is sponsored by NIST and the National Science Foundation.

Summer Undergraduate Researchers
Joseph Ashley, Radford University
Jing Chen, City College of New York
Benjamin Grisafe, The University at Albany-SUNY
Collin Baker, University of the District of Columbia
Eric Marksz, University of Pittsburgh
Benjamin Pound, Utah State University
Sergei Wallace, University of Alabama
Maximilliano Silva-Feaver, Santa Clara University

CNST Undergraduate Researcher
Noah (Adam) Bern, Cornell University

Research Interns
Roger Kardys, Rensselaer Polytechnic Institute
Chris Detrick, The University at Albany-SUNY



The CNST SURF students were among 176 at NIST attending seminars, going on lab tours, and presenting their work at an end-of-summer colloquium. **Clockwise from top right:** Marksz, Chen, Ashley, Baker, Pound, Grisafe, Wallace, and Silva-Feaver.

HENRI LEZEC NAMED NIST FELLOW

CNST Project Leader Henri Lezec was named a NIST Fellow in recognition of his contributions as an internationally recognized thought leader in the fields of nanoplasmonics and metamaterials, materials that do not obey the normal rules of light reflection and refraction. The honor also recognizes his work in the application and development of focused ion-beam nanofabrication methods and for leading NIST programs in all of these areas, helping to make NIST a national focus for improving the nations' advanced technology and manufacturing economy. The title "NIST Fellow" is reserved for the NIST's leading scientists and engineers. It recognizes and further enables the work of scientific and technical staff who operate at the highest level of achievement and impact in contributing to the NIST mission.

Lezec, who joined NIST in 2007, received his Ph.D. from MIT in 1992 and has held research positions at NEC Fundamental Research Laboratories in Japan, Micrion Corp., the Centre National de la Recherche Scientifique in France, and at the California Institute of Technology. He has investigated a broad range of topics associated with the interaction of light with nanoscale structures. He is widely known for his research observing and explaining how plasmons can control the propagation of light through nanoscale apertures, and for creating and measuring metamaterials (materials that have a negative refractive index).

Lezec is a prolific writer of important publications and a sought-after invited speaker. He has published over 100 papers, including three letters in *Nature* and four in *Science*, as well as four in *Physical Review Letters* and six in *Nano Letters*. His papers have been cumulatively cited over 13,000 times with more than 20 papers receiving over 100 citations. He has 38 granted patents (13 U.S., 17 Japanese, 5 European, 2 Canadian, 1 Taiwanese), with an additional 11 patents pending (including 2 U.S.). His work has been recognized with a fellowship in the Optical Society of America in 2010, and with the award of the prestigious Julius Springer Prize for Applied Physics in 2011.

MARC CANGEMI WINS NIST SIGMA XI OUTSTANDING SERVICE AWARD FOR SUPPORTING USERS OF THE CNST NANOFAB

Marc Cangemi, a Process Engineer in the CNST NanoFab Operations Group, has been awarded the 2014 Sigma Xi Outstanding Service in Support of NIST Research Scientists Award for "skilled, cooperative, and helpful support of NIST and external users of the CNST NanoFab." First awarded in 1988, the award acknowledges outstanding contributions by a staff member in support of scientists at NIST.

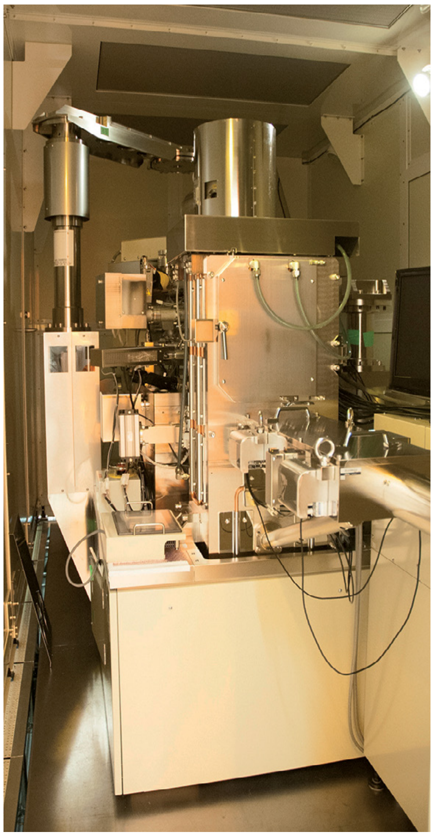
The award was presented by the NIST Chapter of Sigma Xi at their annual banquet on June 4, 2014 at the Dogfish Head Restaurant. In nominating him for the award, NanoFab Manager Vincent Luciani noted that Marc was "a user's best friend in the NanoFab" and also an "extraordinary role model to senior professionals, as well as an inspiration to development staff at the beginning of their careers."

In the CNST, Marc is responsible for training and process support for NanoFab users in various nanofabrication areas, including optical photolithography, metrology, deposition, and oxidation. He also establishes the baseline processes related to deposition of thin film materials and optical resists. Marc has a B.S. in Microelectronic Engineering from the Rochester Institute of Technology. Prior to joining NIST he worked for Photronics, Inc., where he was responsible for the development and characterization of advanced and prototype photomasks.

COMING SOON: NEW TOOLS IN THE NANOFAB

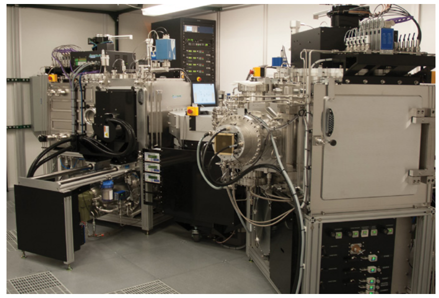
The CNST has acquired a range of new tools which will become available to NanoFab users in the coming months.

Direct Write E-Beam Lithography System



A new JEOL 6300-FS direct write electron beam lithography system has been installed in the cleanroom, doubling the NanoFab's capability in e-beam lithography. The new state-of-the-art system offers high resolution exposure capability and accommodates batch handling of substrates. The system is available to users through the NEMO system. For additional information, contact Rich Kasica, 301-975-2693, rkasica@nist.gov.

Sputter Cluster System



The 4-Wave Sputtering Cluster System (SCS) is expected to be available to users by January 2015.

The CNST has received delivery of the 4-Wave Sputtering Cluster System (SCS). Installation is underway and the tool is expected to be available to users by January 2015. This system will provide users physical deposition capability using ion beam deposition or biased target deposition, resulting in the densest available thin films deposited at room temperature. The SCS has cassette-to-cassette and robot wafer handling, a load lock, and 12 ready-to-deposit materials to provide users clean films on substrates ranging from small pieces up to 200 mm diameter wafers. For additional contact Gerard Henein, 301-975-5645, gerard.henein@nist.gov.

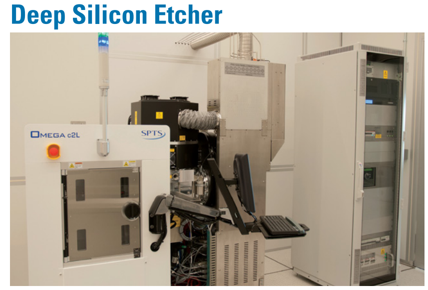
Lithography Coater System

A new Suss Microtec ASC200 Gen 3 automated resist coater is now available to users in the NanoFab cleanroom. This system is able to perform spray and spin resist coating with automated wafer handling and resist baking. It is designed to be able to apply high quality resist film on a wide range of substrate shapes, sizes and topologies with consistent and uniform results. This new resist coater enhances the quality, repeatability and throughput of NanoFab precision lithographic imaging. For additional information, contact Liya Yu, 301-975-4590, liya.yu@nist.gov.

High Resolution Field Emission Scanning Electron Microscope

The CNST has purchased a JEOL JSM-7800F field emission scanning electron microscope (FE-SEM) which will be installed in the NanoFab cleanroom in spring 2015. The JSM-7800F is a research grade, extremely high resolution thermal Schottky type SEM which provides high resolution imaging for any type of sample. It also maintains long-term beam stability for analysis, as well as high beam currents, and high resolution. This is a high performance FE-SEM that can be used to observe the finest structural morphology of nanomaterials at 1,000,000× magnification with better than 1 nm resolution. It has excellent low voltage imaging capability, enabling users to image resist coated wafers, quartz wafers, and other non-conducting samples without needing a conductive coating. It can handle wafers up to 200 mm in diameter and obtain images from the entire wafer. The FE-SEM will be located in the NanoFab cleanroom to allow easy imaging of wafers between process steps as well as imaging routine samples. For additional information, please contact Kerry Siebein, 301-975-8458, kerry.siebein@nist.gov.

Deep Silicon Etcher



The CNST has purchased a new SPTS Omega c2L Rapier deep silicon etcher (DSE) which is now available to users in the NanoFab cleanroom. The new DSE can handle up to 200 mm diameter silicon wafer and can etch faster than the current deep silicon etcher in NanoFab. This new DSE also can provide smoother sidewall and better end point detection. This tool can be used to fabricate three-dimensional structures in silicon (Si) with vertical sidewalls with very high aspect ratios (greater than 50:1). Applications include fabricating micro/nano electromechanical systems (MEMS/NEMS) such as accelerometers, ink jet heads, pressure sensors, gyroscopes, microphones, microactuators, and lab-on-chip devices. For additional information, contact Lei Chen, 301-975-2908, lei.chen@nist.gov.

Sheet Resistance Mapping System

The CNST has purchased a Four Dimensions 280DI 4-point probe sheet resistance mapping system which is expected to be available to users January 2015. The tool will use the four point probe technique to measure sheet resistances ranging from 800 GΩ down to 1 mΩ. The automated stage and software provide mapping measurement capability of up to 5000 points per wafer on substrates ranging from 200 mm diameter wafers down to 25 mm diameter wafers with a measurement speed of a few seconds per point. For additional information, contact Gerard Henein, 301-975-5645, gerard.henein@nist.gov.

Downstream Plasma Asher System

The CNST has purchased an ULVAC Solutions ENVIRO-1Xa downstream plasma asher which will be available to users in spring 2015. The downstream plasma asher will remove more than 1 μm of photoresist per minute and clean substrates without damaging their surfaces. The tool forms the plasma remotely and, to protect the surfaces, the desired particles are channeled to the wafer to ensure that the highest energy ions in the plasma do not impact the substrate. For additional information please contact Marc Cangemi, 301-975-5993, marc.cangemi@nist.gov.

Single Wafer Spray Acid System

The CNST has purchased three SSEC model 3300ML spray acid cleaning systems to support RCA and Piranha processes in the NanoFab cleanroom. The tools are expected to be installed in spring 2015. These tools will provide automated single wafer cleaning processes without exposing users to chemicals. They will replace the current immersion cleaning process. This will eliminate cross contamination between wafers, and provide better wafer cleaning capability. The three systems can accommodate substrates ranging from 200 mm diameter wafers to small pieces. In addition, the tools are capable of delivering, mixing, and heating chemical solutions on demand. For additional information, contact Jessie Zhang, 301-975-4565, chen.zhang@nist.gov.

CNST BRINGS INSTRUMENT DEVELOPERS TOGETHER WITH RESEARCHERS FROM INDUSTRY

In October, the CNST, working collaboratively with Nebraska-based ellipsometer manufacturer J.A. Woollam Co., hosted a three-day workshop that brought together Woolam's instrument developers with the leading scientists and engineers from industry who use the CNST NanoFab. The workshop focused on methods for extracting data from ellipsometers, instruments that measure the properties of layered thin films frequently used in manufacturing. It included side discussions about the development needs for next generation ellipsometry tools. Participants included researchers from large companies, like Raytheon and ExxonMobil, small companies, academia, the Department of Defense, and metrology experts from NIST.

CNST Center for Nanoscale Science & Technology

CENTER FOR NANOSCALE SCIENCE AND TECHNOLOGY

The CNST is a national user facility purposely designed to accelerate innovation in nanotechnology-based commerce. Its mission is to operate a national, shared resource for nanoscale fabrication and measurement and develop innovative nanoscale measurement and fabrication capabilities to support researchers from industry, academia, NIST, and other government agencies in advancing nanoscale technology from discovery to production. The Center, located in the Advanced Measurement Laboratory Complex on NIST's Gaithersburg, MD campus, disseminates new nanoscale measurement methods by incorporating them into facility operations, collaborating and partnering with others, and providing international leadership in nanotechnology.

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SUPPORTING THE DEVELOPMENT OF NANOTECHNOLOGY FROM DISCOVERY TO PRODUCTION

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VISIT THE CNST BOOTH AT THE

ARPA-E ENERGY INNOVATION SUMMIT

GAYLORD HOTEL AND CONVENTION CENTER
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FEBRUARY 9 – 11, 2015

NANOFAB SCHEDULE FOR THE WINTER HOLIDAYS

DAY	DATE	EVENT	STAFF SUPPORT
Wednesday	December 24th	Christmas Eve	7 am to 3 pm
Thursday	December 25th	Christmas Day	None
Friday	December 26th	Day after Christmas	None
Wednesday	December 31st	New Year's Eve	7 am to 3 pm
Thursday	January 1st	New Year's Day	None
Monday	January 19th	Birthday of Martin Luther King, Jr.	None
Monday	February 16th	Washington's Birthday	None

When the NanoFab is closed, after-hours access using the buddy system is available with advance approval.